

A New Six-Degree-of-Freedom Force-Reflecting Hand Controller for Space Telerobotics

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Abstract

A new six-degree-of-freedom universal Force-Reflecting Hand Controller (FRHC) was designed for use as the man-machine interface in teleoperated and telerobotic flight systems. The features of this new design include highly intuitive operation, excellent kinesthetic feedback, high-fidelity force/torque feedback, a kinematically simple structure, mechanically decoupled motion in all six degrees of freedom, good backdrivability, and zero backlash. In addition, the new design has a much larger work envelope, smaller stowage volume, greater stiffness and responsiveness, and better overlap of the human operator's range of motion than do previous designs.

This paper briefly describes the utility and basic operation of a new, flight prototype FRHC called the Model X. The design heritage, general design goals, and design implementation of this advanced new generation of FRHCs are presented, followed by a discussion of basic features and the results of initial testing.

Introduction

Many future space operations anticipate the extensive use of robot manipulators and servicers to assist astronauts and scientists in the exploration of space and development of a space-based infrastructure.

Although robotics is a rapidly developing field, for decades to come there will be many applications and tasks that are far too complex and unstructured to be performed completely by unsupervised autonomous robots. Therefore, the need for direct human supervision and control of these advanced robotic systems will continue in the foreseeable future. This is also true in terrestrial applications, such as undersea exploration, remote defense technologies, and various tasks in the nuclear industry. Often it is necessary to have the human operator physically removed from the actual worksite, remotely supervising and guiding the robot in the performance of a difficult or dangerous task. One of the key problems facing the designers of human-supervised robotic systems is how to make these sophisticated machines user friendly--how to facilitate human interfaces with these complex remotely operated (teleoperated) machines. To help solve this problem, JPL has developed a unique man-machine interface known as the Force-Reflecting Hand Controller.

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The FRHC can be used by a human operator to reposition the mechanical arm of a remote robot (telerobot). This operation is performed by simply grasping the FRHC's handgrip and moving it in a desired direction and rate. The remote robotic arm will respond by mirroring the operator's every move. At the same time, if the remote arm comes in contact with, or applies forces to, objects in the remote worksite, then the FRHC mechanism is actuated and the human operator is able to physically feel scaled representations of forces and torques that the remote robot's arm is applying. Laboratory experiments have shown that this type of force feedback information significantly increases an operator's task performance and can prevent damage to the manipulator or worksite [1]. This paper describes an advanced new, flight prototype FRHC recently built at JPL called the Model X. (See Figure 1.)

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|--------------------------|--------------------------|----------------------|--------------------|
| 1. Mounting Stand | 5. Joint 2 Sector Pulley | 9. Link 2 | 13. Joint 6 Pulley |
| 2. Base | 6. Joint 4 Motor | 10. Joint 3 Assembly | 14. Handgrip |
| 3. Joint 1 Sector Pulley | 7. Joint 5 Motor | 11. Link 3 | |
| 4. Joint 2 Motor Shaft | 8. Joint 6 Motor | 12. Joint 5 Pulley | |

Figure 1. The Model X Force-Reflecting Hand Controller

Design Heritage

For many years, researchers have worked to develop a useful and intuitive human interface to teleoperated machines [2,3,4,5]. For more than a decade, JPL has pioneered work in the field of teleoperation and has contributed greatly to the general body of scientific and engineering knowledge about these systems.

In the late 1970s J.K. Salisbury (presently at MIT) in collaboration with A.K. Bejczy of JPL developed a new "universal" force-reflecting master for use in bilateral control of teleoperated systems [6,7]. Since then, three generations of this design have been built and integrated into various telerobotic research environments. The most recent edition is called the "Model C FRHC." Collectively, these hand controllers have undergone several years of testing [1,8].

In 1988, JPL began to look seriously at an opportunity to join a West German flight project called ROTEX (RObotic Technology EXperiment). The proposed venture would require JPL to supply a flight qualified force-reflecting hand controller complete with stand alone electronics and control software. The endeavor was short lived however, and was eventually canceled due primarily to international scheduling and budgetary conflicts. Nevertheless, the effort lasted long enough for the development of two significant operational prototype components: the flight hand controller and its control electronics [9].

This new force-reflecting hand controller was dubbed the "Model X FRHC". A conceptual design for the Model X began in 1986 under W.T. Townsend, who at the time was a post-graduate student of Salisbury and assigned to JPL. The goal of Townsend's work was to investigate alternative FRHC design concepts and suggest an improved version that could eventually be flight qualified [10]. The present design of the Model X was significantly influenced by both Townsend's work and that of Salisbury, inheriting many of their design features and incorporating several new ones.

General Design Goals

The Model X FRHC was developed to meet design requirements stemming from four basic sources.

First, the Model X began as a specific flight project with several functional requirements and constraints. These included a) sense positional changes in X, Y, Z directions, and roll, pitch, yaw orientations, b) apply up to a 17.8 N (4 lb) output force and a 0.452 N·m (64 in·oz) torque to an operator, c) provide a 0.254 x 0.254 x 0.254 m (10 x 10 x 10 in) work volume, which is relatively small due to the limited operating space of this particular flight experiment, d) use an upright, vertical, mounting configuration in order to utilize the one feasible mounting location available for this particular flight experiment, e) allow full operation in both zero-g and at a ground station, in one-g, without external modifications such as adding counter weights, f) stow within a Space Shuttle mid-deck storage locker, g) use a limited amount of power, and h) have a low overall mass.

Secondly, as an anticipated flight project there were several stringent flight qualification requirements. These included a) withstand launch and landing loads, b) use flight crew cabin

approved materials, c) no sharp edges on parts and minimize part count, and d) provide for quick emergency stowage.

The third basic source of design requirements came from the fact that there were several features of existing hand controllers that were to be incorporated into the new Model X design. These included a) highly intuitive operation, b) low friction, c) no backlash, d) high backdrivability, e) simple kinematics, f) low, semi-isotropic inertias, and g) mechanically decoupled degrees of freedom.

Finally, the fourth basic source of functional requirements came from the desire to incorporate a few enhancements over previous hand controller designs. These included a) higher structural stiffness, b) a larger work volume, and c) optimization of the joint/link configuration to allow better overlap of the human operator's range of motion without interfering with other operator control station functions.

General Design Implementation

During establishment of the flight experiment functional requirements and constraints several conceptual designs for a flight qualifiable force-reflecting hand controller were analyzed until a highly promising candidate was found.

One of the first activities in the detailed design process was to determine initial link lengths, based on operational and stowage requirements. A static load analysis was performed to estimate the joint torques necessary to satisfy the hand controller force/torque output requirements. Following this, the motor type and size, along with the corresponding transmission drive ratios, were selected by balancing several constraints, namely: produce the required joint torques, minimize friction, stay within power allocations, consider flight heritage, and delivery times. Brushless DC torque motors were selected with 1000 line, dual quadrature, incremental optical encoders mounted directly on their shafts. Some relevant design parameters are listed in Figure 2.

JOINT	Joint Range* (degrees)	Motor Stall Torque** N·m (in·oz)	Transmission Drive Ratio	Output Joint Torque N·m (in·oz)
1	± 25	0.821 (116.3)	16.0 : 1	13.120 (1858)
2	+ 37/ - 58	0.821 (116.3)	28.0 : 1	23.056 (3265)
3	± 80	0.606 (85.8)	18.3 : 1	13.784 (1952)
4	± 175	0.288 (40.8)	2.3 : 1	0.664 (94)
5	± 175	0.288 (40.8)	2.3 : 1	0.664 (94)
6	± 170	0.086 (12.3)	8.0 : 1	0.692 (98)

* Variations from the standard vertical mounting configuration with
Links 1, 2, and 3 all at 90 degrees w.r.t. each other (as shown in Figure 4)

** Higher peak torques can be output for shorter periods of time.

Figure 2. Joint Actuator Parameters

Pulleys and steel-cables were used in the actuator transmission design. A novel new steel-cable routing scheme was implemented that allowed several significant design features. These features are discussed in the "Basic Features" section of this paper.

The overall hand controller mechanical stiffness was a primary concern during the design process. This is evident at several critical locations throughout the design. In the design of Joint 1 and Joint 4 a single preloaded, gothic-arch, x-type bearing was used. Joints 2 and 3 were designed with a matched pair of preloaded, back-to-back duplex bearings. Links 2 and 3 are made of aluminum tubing with a square cross-sectional shape which is significantly stiffer than round tubing of the same basic size and material. The steel transmission cables, used in all six joints, are pretensioned. Each joint steel-cable circuit can be accurately pretensioned which is an enhancement over previous designs. The transmission circuits for Joints 1 and 2 were designed with double spans of steel-cable in order to reach desired stiffness levels. Joint 3 required a 3-stage drive reduction design in order to meet stiffness goals. (The other five joints have only single stage transmissions.)

The design, fabrication and first complete assembly of the Model X Hand Controller was performed in seven months. A 3-D, solids-molding, mechanical CAD workstation was used for the entire design and some of the analysis work.

Basic Design Features

As indicated in the abstract to this paper, the Model X design has successfully incorporated many of the design goals stated above. Features of the Model X are further discussed here.

The Model X is considered a "universal" hand controller because it can be used with robot manipulators that are structurally dissimilar to one another and to the Model X. The fact that the Model X has "six degrees-of-freedom" (6 DOF) is important because this enables it be used to control robot arms, or other objects, in the six dimensions required to fully specify a unique position and orientation (i.e., X, Y, Z directions and roll, pitch, yaw orientations).

The Model X provides the human operator with "excellent kinesthetic feedback." The act of moving a telerobot's mechanical hand in the performance of a task is directly correlated to the physiological motor sensations that would occur if the operator were performing the task with his own hand. The intrinsic eye-hand coordination of the human operator is fully utilized, making the performance of the task, at the remote worksite, "highly intuitive" to the operator.

The Model X is capable of producing "high-fidelity force feedback" cues to the human operator. The forces and torques encountered by the telerobot at the remote worksite are faithfully reproduced by the hand controller mechanism allowing the operator to physically feel scaled representations of these remote interactions. The Model X has a good dynamic force output capability. Small feedback forces to the operator are not obscured by friction levels, and yet it can also output relatively large forces. Moreover, the forces and torques transmitted to the operator are crisp and distinguishable.

Minimizing friction in the mechanism was an important consideration during the Model X design. The Model X is run "open loop" (i.e., the actual output forces to the operator are not measured or fed back to the control algorithms), therefore the friction in the mechanism

becomes the limiting factor in determining the smallest commandable output force. This, of course affects the force resolution mentioned above. If the friction levels were too large they could deflect the operator from an intended input trajectory (path) or, in severe cases, they could degrade the backdrivability of the hand controller. The Model X has relatively low friction levels as shown in the "Initial Testing and Evaluation" section.

Using guide pulleys and steel-cables, as opposed to gear trains and drive shafts, made it possible to produce a mechanism with virtually no backlash. Having "zero joint backlash" (or play) is an important feature because it eliminates position deadband in the mechanism. This helps the stability of the control system.

The novel new steel-cable routing scheme used in the actuator transmission design allowed several very significant design features. For instance, it allowed all six joint motors, which make up almost half the Model X's overall mass, to be mounted near the base of the hand controller. This greatly reduced the inertial effects caused by the mass of these motors. The cabling design uses a minimum number of guide pulleys between the motor input and the joint output pulleys which helps to reduce mechanism friction.

The new steel-cable routing scheme also allowed the Model X to be designed with very "simple kinematics." This means that the Model X is relatively simple to describe mathematically. Computationally, a robot manipulator and a force-reflecting hand controller appear very similar. Many of the control techniques and approaches used in each system are identical. A standard notation for describing the geometric inter-relationships between one joint / link assembly and the next are provided in the Hartenberg/Denavit parameters. (Shown in Figure 3.) There are no joint offsets or link twists and the link lengths remain constant. In addition, five of the joint axes intersect orthogonally to one another and the sixth is parallel. This simplicity helps minimize the time required for a computer to calculate where the center of the Model X's handgrip is, relative to a fixed reference location (forward kinematics). In fact, of six-degree-of-freedom manipulators, the Model X has one of the simplest configurations possible.

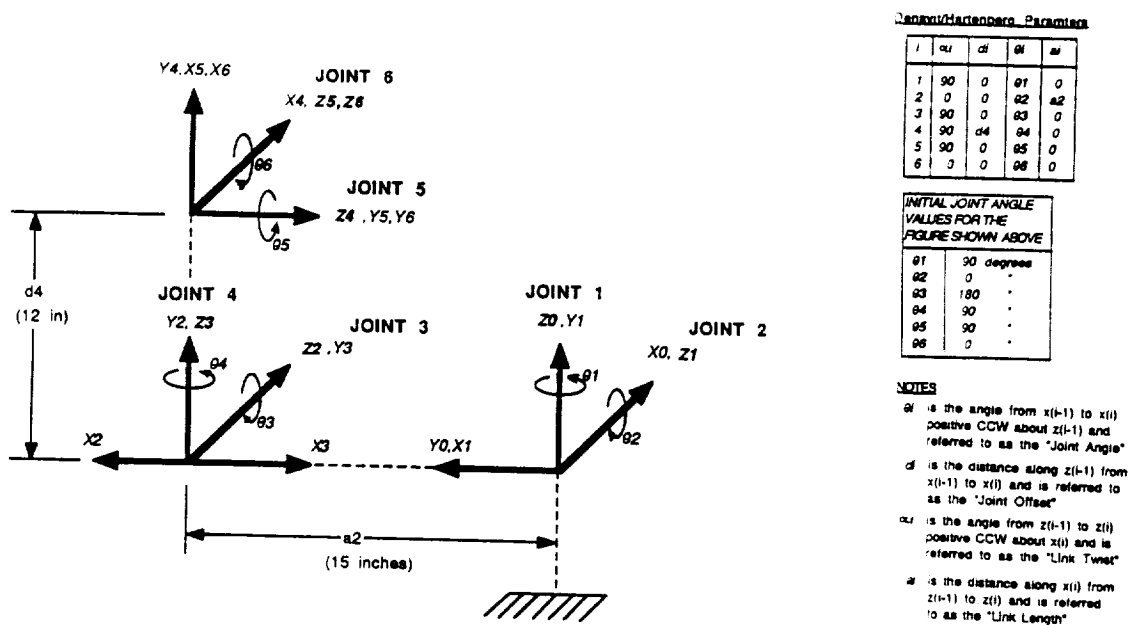


Figure 3. Kinematic Coordinate Assignments and Hartenberg/Denavit Parameters

Even though the Model X has no kinematic offsets the new steel transmission cable routing technique allows the Link 2 assembly to be physically offset from Links 1 and 3. (See Figure 1.) This feature increases the mechanical dexterity and permits the hand controller to fold up into a "small stowage volume" when not in use.

Finally, the steel-cable routing design permits all six joints to be "mechanically decoupled" from one another, that is, each joint rotates completely independent of all others. This helps to simplify the software control algorithms required to activate the Model X.

While the Model X Hand Controller was being designed, great care was also taken to ensure it would have maximum "stiffness and responsiveness." This attention to structural stiffness improves the quality and clarity of the forces the operator feels because it shortens the response time of the mechanism. This also contributes to control system stability. (See stiffness evaluation in the following section.)

The "work envelope" of a hand controller refers to the three-dimensional space through which the operator is able to move the handgrip. A cross-sectional view of the work volume of the Model-X while in the vertical mounting configuration is shown in Figure 4. This cross-section would be rotated ± 25 degrees about the Joint 1 axis to obtain the 3-D work volume.

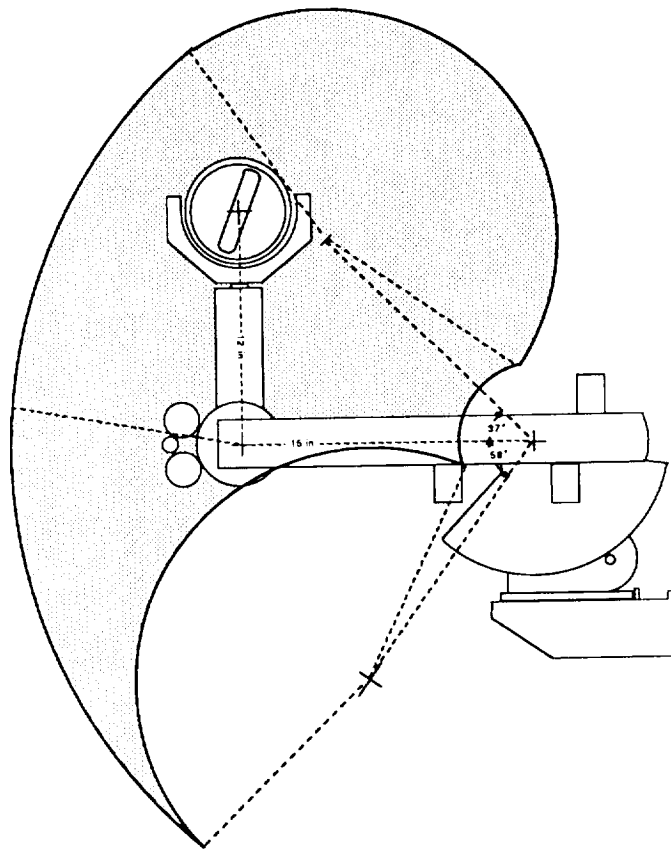


Figure 4. Model X Work Envelope

In special mounting configurations, this work envelope coincides directly with the range of motion for the human operator's arm. (See Figure 5.) This means that the Model X can follow almost any motion of the human operator's hand over its entire reach.

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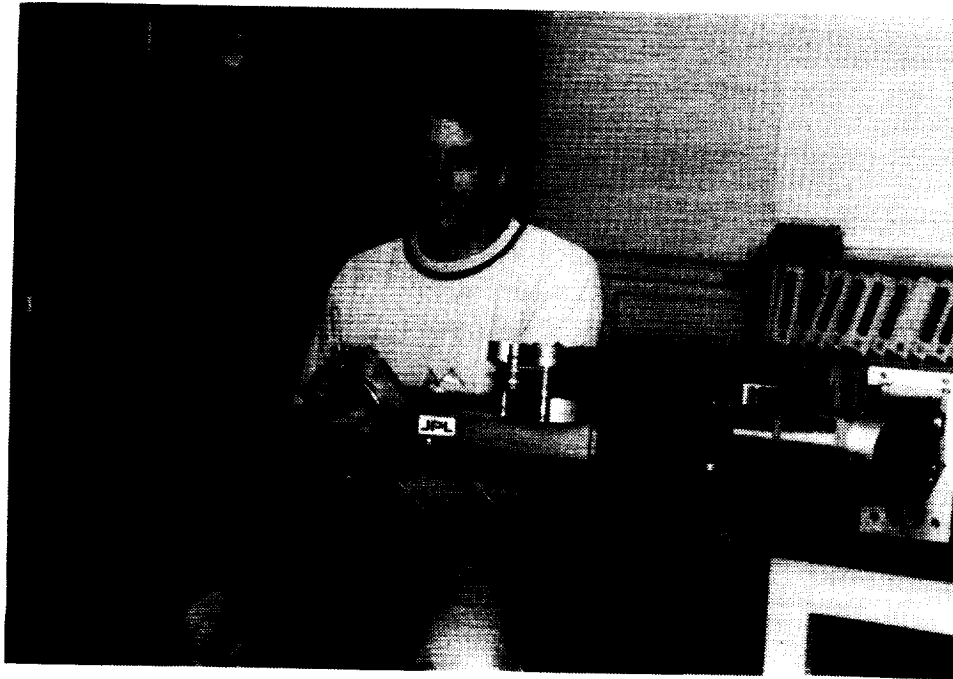


Figure 5. Model X Horizontal Mounting Configuration

Initial Testing and Evaluation

There are several key design parameters that are of particular interest when evaluating the utility and effectiveness of the Model X Hand Controller. These parameters include positional resolution, dynamic range of the force output, friction levels, inertia, backdrivability, backlash, stiffness, dynamic mechanical response, and natural (resonant) frequencies. Together these parameters provide a thorough characterization of the mechanism.

In order to quantify some of these parameters, the Model X has undergone several initial tests and measurements. Although these early test results are preliminary in nature, they provide an encouraging initial verification of the design goals.

The positional resolution (i.e., the smallest detectable motion at the handgrip) changes slightly across the work volume due to the geometry of the Model X. At near full extension, the Model X has its least resolution. In this configuration, the positional resolution is still better than 0.051 mm (0.002 in) and increases as the handgrip is moved closer to the Joint 1 axis.

The dynamic range of output forces and torques provides insight into the quality and clarity of the forces that are "reflected" back to the person operating the Model X. The dynamic range is defined as the maximum commandable output force divided by the minimum. The output forces in the X, Y, and Z directions are position dependent and are inversely proportional to the distance out from the Joint 1 axis. When the hand controller is fully outstretched and operating in gravity (worst case), the Model X can output feedback forces to the human operator ranging from about 0.8 N up to 18.7 N (3 to 67 oz). Larger forces are possible as the handgrip is moved closer to the Joint 1 axis. In space applications, the maximum output forces in the Link 2/Link 3 plane will be significantly higher since there are no gravitational forces to counteract. The orientation degrees of freedom, Joints 4, 5, and 6, can output torques up to 0.664 N·m (94 in·oz).

The Coulomb friction forces (also referred to as static friction) the operator feels at the handgrip will vary throughout the work volume depending again on the effective radius to the axis of rotation (i.e., how far the handgrip is from the Joint 1 axis). With the hand controller near full extension, these friction levels are about 0.8 N (3 oz) in any direction and slightly increase as the handgrip is moved closer to the Joint 1 axis. The friction levels for the three orientation degrees-of-freedom are constant because the effective radius to the joint axis of rotation never changes. These frictional torques are 0.04 N·m (6 in·oz) about Joints 4 and 5, and 0.09 N·m (13 in·oz) about Joint 6.

Since the Model X was designed for space flight, the overall mass was kept as small as possible without compromising structural ruggedness. It has a total mass of 14.5 kg (32 lb). The motors are mounted near the base of the hand controller, which greatly reduces their inertial effects. The four motors mounted on Link 2 are evenly distributed about the Joint 2 axis. This causes the center of gravity for Link 2 to be only 40.6 mm (1.6 in) from the Joint 2 axis of rotation which helps to reduce the moment of inertia for the link. The low overall inertia and friction levels result in the hand controller mechanism being very backdrivable.

At over 0.1133 m³ (4 ft³), the Model X has a work envelope that more than doubles that of previous hand controllers. (See Figure 4.) The actual work envelope is much larger than that specified in the functional requirements of the original flight project. This was done in order to maintain the applicability of the Model X design to a wide variety of tasks. Even with a much larger work volume the Model X can still be folded up and compactly stowed within a 0.051 m³ (1.8 ft³) volume, which is smaller than previous designs.

The Model X has a rugged structural design that is necessary for the rigorous demands of space flight. The mechanical stiffness of the device also plays a roll in establishing the fidelity and quality of feedback forces to the human operator. Measuring the compliance of a mechanism, which is the inverse of its stiffness, provides us with a good estimate of this important parameter. Initial tests were performed to determine the radial compliance for critical joints. These measurements were made by positioning the hand controller in a desired configuration and rigidly locking the motor shafts. A precision dial indicator was placed in contact with the mechanism at a known radius from the joint axis. A known static load was applied to the hand controller and the corresponding deflection was measured. (See Figure 6.)

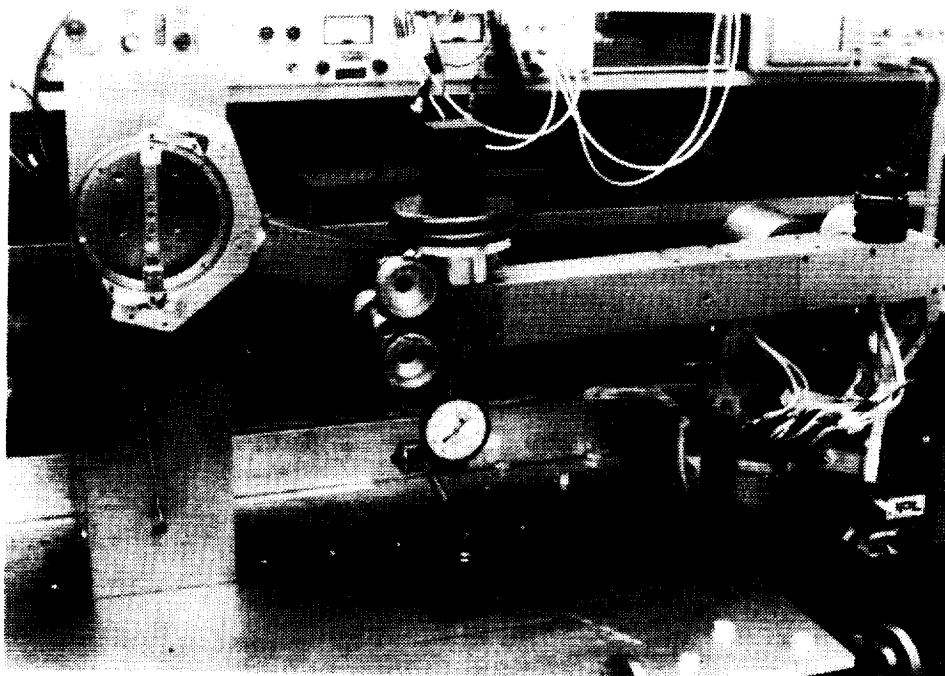


Figure 6. Joint 2 Radial Compliance Measurement

This measurement of the overall radial compliance of the joint combines several sources of structural compliance found in the mechanical system (e.g., actuators, transmissions, bearings, and link bending) and assumes them to be concentrated along the joint axis.

From these data an approximate torsional spring constant for the joint was determined. For example, under a 41.8 N (9.4 lb) static test load, there was a 0.81 mm (0.032 in) deflection at the end of Link 2. This represents a torsional spring constant (k_t) about the Joint 2 axis of more than 222.6 N·m/deg (1970 in·lb/deg). The natural frequency (f_n) can be approximated by evaluating the following equation:

$$f_n = \frac{1}{2\pi} \sqrt{\frac{K_t}{I}}$$

where I is the combined moment of inertia for Links 2 and 3 about the Joint 2 axis. Evaluating this equation yields an initial estimate of the structural natural frequency, about the Joint 2 axis, of over 21 Hz.

A different set of tests were performed in order to more directly examine the mechanical response dynamics and resonant frequencies of the Model X. The Model X is a fairly complex multi-degree-of-freedom mechanism and it inherently behaves in a complex and nonlinear way to traditional frequency response testing methods. An initial estimate, however, can be inferred by examining the output force dynamics of individual joints when subjected to a step change in input.

Joint 1, for example, was tested in the following manner. The hand controller was positioned in its fully outstretched (worst case) configuration. This configuration was maintained by locking the motor shafts of Joints 2 and 3. Only Joint 1 was free to move. The Joint 1 motor was connected to a single-axis motor driver box. This driver box generated a 212 Hz PWM signal that could be adjusted from about 0.2% duty cycle up to 99.8% full power. It also provided a motor direction change toggle line. To measure the output force of the Model X the handgrip was replaced with a single-axis force sensor. This force sensor was then rigidly mounted to a restraint fixture which provided a rigid surface to push against when the Joint 1 motor was energized. (See Figure 7, but note that it does not show the hand controller fully extended.) Switching the motor direction toggle line from low to high caused a step change in motor output torque from cw to ccw and resulted in a step change in the state of the mechanical system. The dynamic output force signal, read by the force sensor, and the motor direction toggle line were displayed on a digital oscilloscope. (See Figure 8.)

Joint 2 was tested in a similar manner and its dynamic mechanical response is depicted in Figure 9. Joint 3 was further isolated for testing by physically removing the entire Link 2/ Link 3 and Handgrip Gimbal Assembly from the rest of the mechanism and rigidly mounting Link 2 to a metal table top. The dynamic mechanical response for Joint 3 is shown in Figure 10.

These frequency response tests confirmed our expectation that the mechanical system would behave in a complex and non-linear way. However, by assuming only moderate simplification, an initial estimate of the damped natural frequency for Joints 1, 2 and 3 can be approximated using various standard approaches [11]. For example the damped natural frequency (Ω_d) can be simply estimated by determining the peak time (t_p), which is the time required for the response to reach the first peak of overshoot, and dividing it into pi (π).

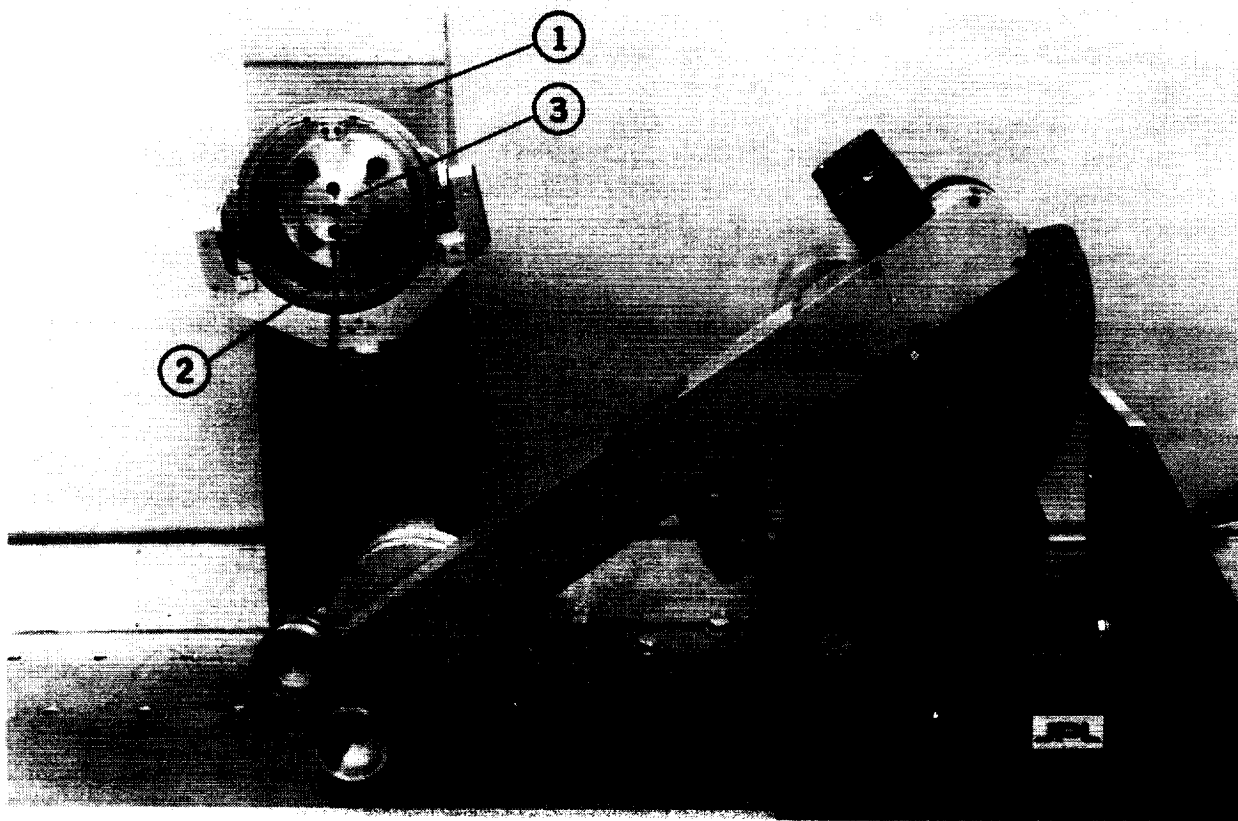
$$\Omega_d = \frac{\pi}{t_p}$$

The natural frequency about a joint can also be initially estimated by measuring the elapse time for several successive peaks and then finding an average peak to peak period. The reciprocal of this value would be an approximate measure of the natural frequency.

These methods indicate natural frequency values, for the Model X, within the following ranges:

Joint 1 = 27 to 29 Hz
 Joint 2 = 27 to 33 Hz
 Joint 3 = 37 to 40 Hz

These values are approximately two to three times higher than those found in previous hand controller designs.



1. Vertical Restraint Fixture 2. Single-Axis Force Sensor 3. Force Sensor Mounting Bracket

Figure 7. Joint 1 Dynamic Mechanical Response Test Apparatus

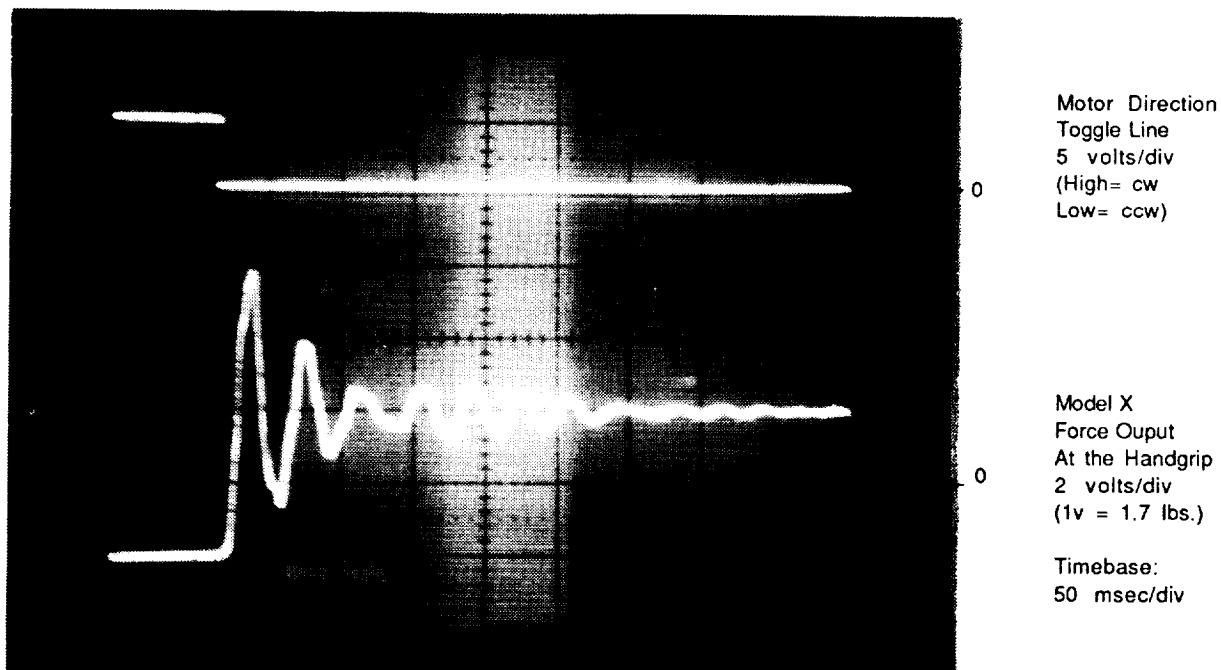


Figure 8. Joint 1 Dynamic Response to a Step Input

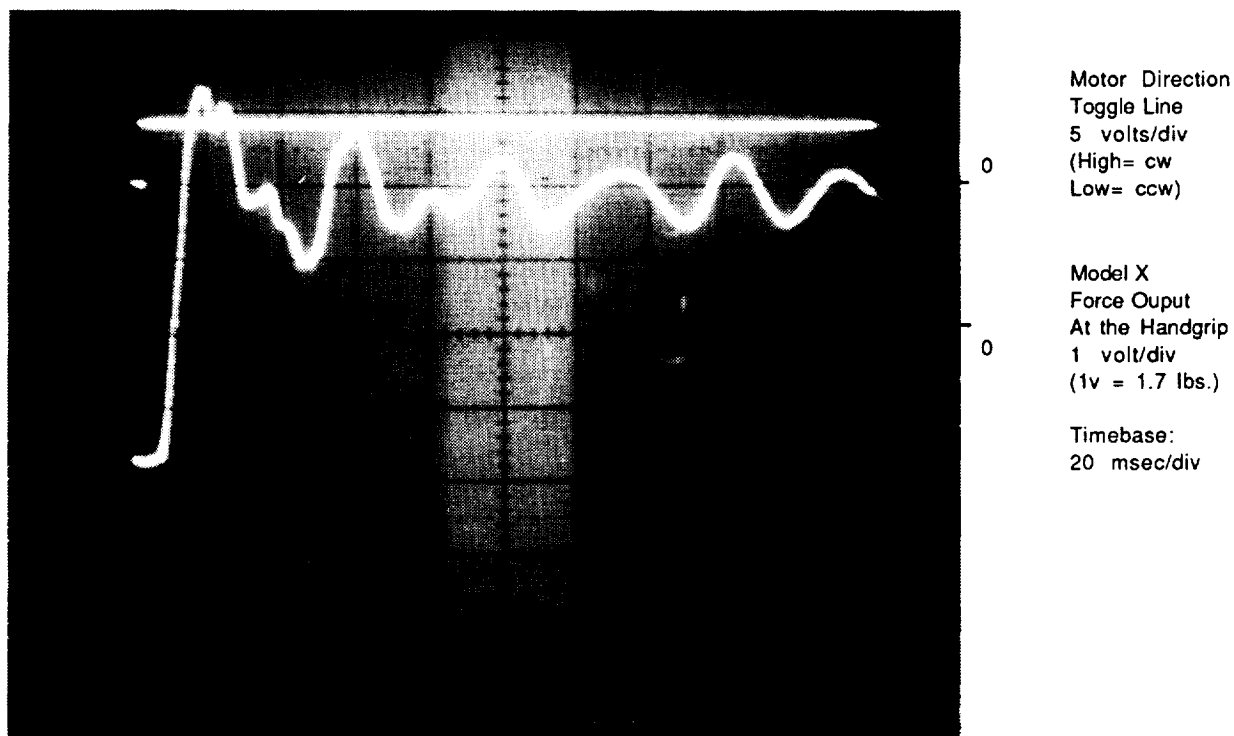


Figure 9. Joint 2 Dynamic Response to a Step Input

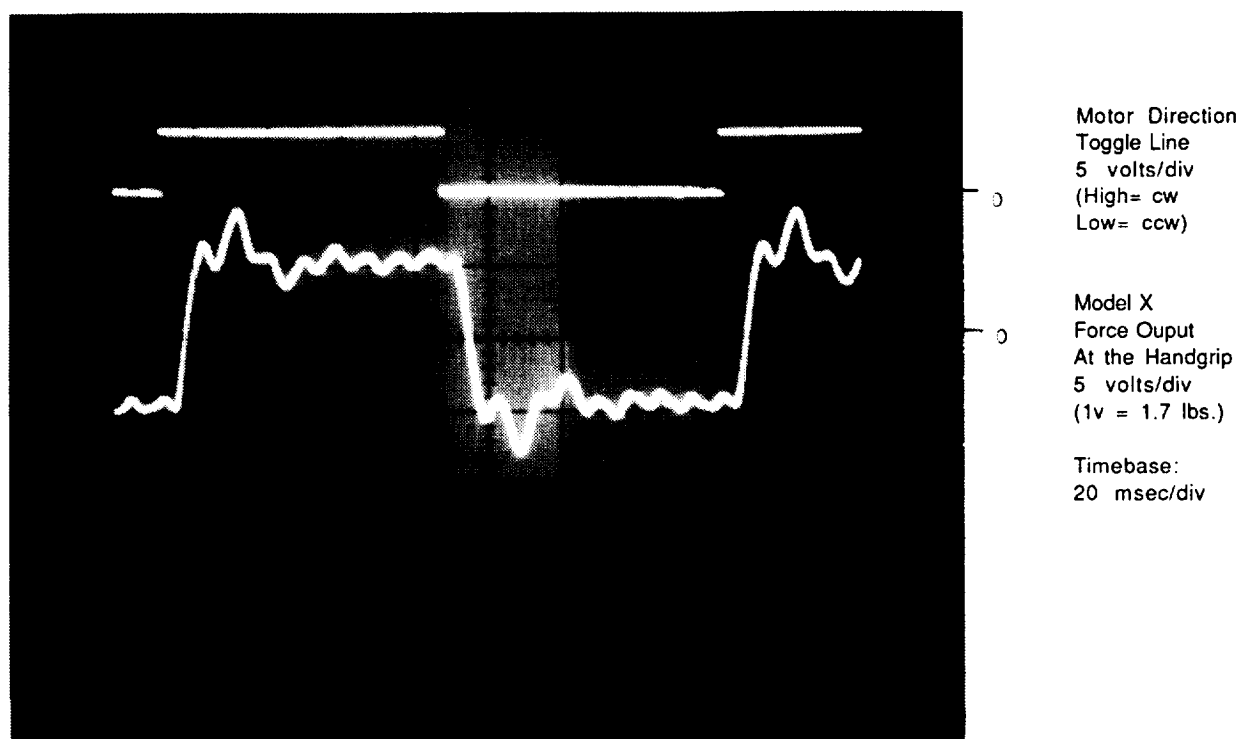


Figure 10. Joint 3 Dynamic Response to a Step Input

Summary

The Model X FRHC meets or exceeds many of the original design goals. It is a unique step forward in universal force-reflecting hand controller design. It combines many of the intrinsically desirable features of previous designs such as highly intuitive operation, low friction, low inertia, high backdrivability, no backlash, simple kinematics, and mechanically decoupled joint rotation. In addition, it is a rugged, flight-worthy device, with high stiffness and structural natural frequencies in excess of 25 Hz, allowing the Model X to generate high-fidelity force feedback cues to the human operator. It has an overall mass of only 14.5 kg (32 lb). The mechanical transmission incorporates a unique steel cable routing design that provides many beneficial features including the capability of folding the Model X for compact stowage in less than 0.051 m³ (1.8 ft³). With a fully usable work volume of over 0.1133 m³ (4 ft³) it more than doubles the range of motion than that of previous hand controllers especially since it is optimized to coincide with nearly the full range of motion of the human operator's arm.

Other Potential Areas of Application

The Model X Hand Controller is a very intuitive, highly versatile, human interface to complex multi-degree-of-freedom dynamic machines.

As a position input device with force output capabilities, the Model X has been optimized to be the fundamental and natural interface a human operator needs in order to manipulate multi-dimensional spatial relationships where force cues can help associate a coordinated response. As such, the Model X may prove to be a useful human interface in applications other than the control of teleoperated robotic arms.

Areas of possible application of Model X design technologies might include a) new seven, or more, degree-of-freedom redundant robot manipulator design that would have good force control capabilities, b) new pilot interfaces for underwater exploration robots, c) a new helicopter pilot flight control interface, d) nuclear industry applications, e) an RPV ground based flight controller, and f) computer image manipulation.

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References

- [1] "Performance Evaluation of a Six-Axis Generalized Force- Reflecting Teleoperator", B. Hannaford et.al., JPL Publication 89-18 (Internal Document), June 1989.

- [2] "A Force Reflecting Positional Servo-mechanism", Nucleonics, vol. 10 pp. 43-45, November 1952.
- [3] "Force-Reflecting Electrohydraulic Servomanipulator", R.S. Mosher and W. Berthold, Electro-Technology, vol. 66 pp. 138-141, December 1960.
- [4] "Some Work on Manipulator Systems at ANL; Past, Present, and a Look to the Future", Ray C. Goertz, Proceedings of the 1964 Seminars on Remotely Operated Special Equipment, vol. 1 AEC CONF-640508, pp. 27-69.
- [5] "Teleoperators and Human Augmentation", An AEC-NASA Technology Survey, by Edwin G. Johnson and William R. Corliss, NASA SP-5047, Dec 1967.
- [6] "Study of Modeling and Evaluation of Remote Manipulator Tasks with Force Feedback", J.W. Hill, Report 5 & 6, JPL Contract 95-5718 Stanford Research Institute, Menlo Park, CA., 1979.
- [7] "Kinesthetic Coupling Between Operator and Remote Manipulator", A. Bejczy and J.K. Salisbury, Proceedings of the International Computer Technology Conference, ASME, August 1980.
- [8] "Teleoperator Subsystem/ Telerobot Demonstrator: Force Reflecting Hand Controller Equipment Manual", D.A. McAfee and Tim Ohm, JPL D-5172 (Internal Document), January 1988.
- [9] "TRIIFEX Final Report", R.L. Robinson, JPL D-6541 (Internal Document), June 1989
- [10] "Initial Development of the Model X: An Alternative, Compact, Force-Reflecting Hand Controller", W.T. Townsend, Internal JPL Memorandum 347-87-764 (Internal Document), August 1987.
- [11] "Modern Control Engineering", K. Ogata, Prentice-Hall Publishing, pg. 235, 1970.
- [12] "Mechanical Design of Robots", Eugene I. Rivin, McGraw-Hill Book Co., 1988.

